VPI-E-73-15
July 1973

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Prepared for:
U. S. Air Force, Air Force Systems Command
Wright-Patterson AFB, Ohio 45433
Contract No. 33615-72-C2111

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ABSTRACT

The stress freezing technique of photoelasticity was utilized to study the stress intensity variation between full thickness and center slices of compact tension specimens for various crack lengths. Specimen geometries covered an a/w range of 0.3 to 0.7 and for values of w/B of 2 and 3.5 .

Normalized SIF results for geometries within ASTM E 399-72 specifications (i.e. w/B = 2.0, a/w = 0.50) agreed with the ASTM solution to within experimental error. However, for a/w values outside the ASTM range (0.45 to 0.55), experimental results were measurably higher than the ASTM results for w/B = 2.0 and averaged 13% higher for all a/w studied at w/B = 3.5. The center slice SIF was found to be 5 to 10% higher than the through the thickness average on all tests.

CONTENTS

FIGURES

NOMENCLATURE

σ_{ij}	In plane stress components
K_I	Mode I Stress Intensity Factor (lbs/[in]$^{3/2}$)
r,θ	Polar coordinates (inches, radians)
a	Crack length (inches) (see Figure 2)
w, B	Specimen width (inches) (See Figure 2), Specimen thickness (Inches)
τ_{max},τ_m	Maximum shearing stress in plane perpendicular to crack border (psi)
K_{ap}	Apparent stress intensity factor (lbs/[in]$^{3/2}$)
K_{TSCM}	Approximate stress intensity factor (lbs/[in]$^{3/2}$)
n	Fringe order
f	Material fringe value (#/in)
t	Thickness (inches)

INTRODUCTION

A substantial effort, both from the point of view of analysis as well as fracture toughness testing, has been carried out in recent years towards the development of a universal compact plane strain fracture toughness test specimen. The analyses have taken the form of boundary collocation [1]-[5] and finite element solutions [4,5,6]. The correlation of the published results of fracture toughness testing programs is found in References [3] and [7] together with tentative test specifications and procedures. In a discussion in Reference [3], the importance of studying the three-dimensional effects photoelastically was noted. More specifically, the variation in the three-dimensional effect upon the stress intensity factor (SIF) with thickness and crack length was found to be virtually unknown. Although photoelastic stress analysis has been carried out on geometries similar to the current compact tension specimen [8], and the SIF has been estimated for the center slice [9], apparently no study has been directed towards measuring the three-dimensional effect upon the SIF directly for varying thickness and crack length. Moreover, except for the analysis of a highly idealized model [10], analytical studies have been essentially two dimensional. The present investigation was undertaken to study this effect photoelastically for a range of compact tension specimen crack lengths and thicknesses of interest to ASTM and agencies utilizing the compact tension test in order to determine the feasibility of extending the specimen geometrical ranges prescribed by ASTM E 399-72.

ANALYTICAL CONSIDERATIONS

Photoelastic studies of crack tip stress fields have been carried out by a number of investigators [11]-[20]. One of the major difficulties in

such studies has been the problem of extracting valid SIF values from the photoelastic data. This problem has received considerable attention recently by Marloff and his associates [9], Kobayashi and his associates [21-24], and more recently by the author and his associates [25]-[29]. The author and his associates have developed two methods for extracting the SIF which have been used in a wide variety of problems. One of these methods, called the Taylor Series Correction Method (TSCM), will be employed in the present study. The philosophy and use of the method are described in the sequel.

It is well known that the elastic stresses near a crack tip in a plane normal to the crack border take a familiar singular form which may be written as:

$$\sigma_{ij} = \frac{K_I}{r^{1/2}} f_{ij}(\theta) \quad i,j = x,y \tag{1}$$

where K_I is the stress intensity factor and r,θ are measured from the crack tip as shown in Figure 1. Since σ_{ij} involve singular terms, then the maximum in plane shearing stress:

$$\tau_{max} = \frac{1}{2}\left[(\sigma_{yy} - \sigma_{xx})^2 + 4\tau_{xy}^2\right]^{1/2} \tag{2}$$

will also involve singular stresses. The authors have shown [25] that the blunted zone created by stress freezing photoelasticity near a crack tip creates a nonlinear zone very near the crack tip, but this zone is very local and light reflections from the crack tip ordinarily preclude measurements this close to the crack tip. On the other hand, there is no way to determine precisely how far away from the crack tip one can be before nonsingular terms in the stress description begin to contribute appreciably to the photoelastically measured τ_{max}. Since fringe loops around a crack tip tend to spread furthest along a line approximately in

a direction normal to the crack surfaces and passing through the crack tip, data are always taken along this line, reducing τ_{max} to the form:

$$\tau_{max} = \tau_{max}(r) \tag{3}$$

In order to account for boundaries other than crack surfaces themselves, TSCM expresses τ_{max} in the form:

$$\tau_{max} = \frac{A}{r^{1/2}} + \sum_{N=0}^{M} B_N r^N \tag{4}$$

A computer program has been written to receive input data in the form of τ_{max}, r from the photoelastic data, and to compute A, B_N from the data using a least squares procedure beginning with only the first term (i.e., A) then A, B_0, then A, B_0, B_1, etc. recomputing A each time until the Mth term contributes an amount to τ_{max} less than the estimated experimental error. In this region, Eq. (4) is truncated and $A = K_I/(8\pi)^{1/2}$ is determined. There is no specific truncation criterion and some judgement on the part of the investigator is required here. The convergence of the program is verified in reference [27].

For two-dimensional problems, the method corresponds to the application of the Williams Stress Function along $\theta = \pi/2$. Details of the program are found in Reference [27].

THE EXPERIMENTS

A set of photoelastic experiments was designed to study the influence of crack length upon the stress intensity factor for two thicknesses and the three-dimensional effects thereof. The basic geometry of the test specimens is given in Figure 2 and the dimensions are found in Table I. The use of the 30° notch to simulate the crack tip stress field was sug-

gested by the result of investigations in Ref. [30] and was verified by comparing pilot test results with Wilson's boundary collocation solution. Pilot tests revealed that, due to the very low threshold value of K_{IC} for the model material above critical temperature, live loads were restricted to very small values and a counterweight was necessary in order to maintain Mode I loading on the crack tip. The force system consisting of the dead weight of the lower half of the specimen, the counterweight, and the added pin reaction served to intensify K_I. Moreover, the use of full size pins above critical temperature produced erratic results due to variations in the contact surface and frictional effects as the soft material deformed around the pins. In order to alleviate the several difficulties described above, the authors used pins which were approximately one half the hole size for the stress freezing tests and were able to obtain consistent results. Furthermore, the value of K_I was established from through the thickness room temperature fringe patterns for each test (using full size pins and much larger loads than those at stress freezing temperatures) and the thickness effect was obtained by stress freezing in a subsequent test on the same specimen. This approach implies that the auxiliary loading system consisting of the weight of the lower half of the specimen, the counterweight, and additional pin forces has no influence upon the variation in K_I through the specimen thickness. Pilot tests using only the auxiliary load system with the A-3 geometry support this assumption.

Model manufacture - All models were made from PLM-4B or Hysol 4290 stress freezing photoelastic materials by milling off 50 mils from all surfaces and maintaining ASTM tolerances throughout. All cracks were made with circular saws.

Test procedure - After inspection in the polariscope to insure stress-free specimens, the specimens were loaded at room temperature through full size pins in a dead weight system and through-the-thickness fringe photographs were obtained. Specimens were then counterweighted, hung in the oven and heated slowly to critical temperature (275°F or 300°F). After a thermal soak of about 10 hours, the live load was applied as a dead weight through the lower pin and cooling at a rate of about 2°/hr. was carried out under full load. Upon cooling, the specimen was placed in a tank of oil of the same index of refraction as the model material, and full scale and local fringe photographs were made. A full scale fringe photo through the thickness is shown in Figure 3. Next, a center slice about 0.10 in. thick was removed perpendicular to the crack border, and the fringe photography was repeated utilizing a partial mirror fringe multiplication system. All local fringe shots were made through a telescopic lens producing working prints of about 15 to 20X. A typical slice photo is shown in Figure 4.

RESULTS

A typical set of raw fringe data from the stress freezing tests is shown in Figure 5 together with the curves fitted by TSCM. Data scatter is small and the curves fitted by TSCM fit the data well. In order to obtain a more sensitive assessment of data scatter and to illustrate how TSCM is used to obtain the SIF by extrapolation, the data of Figure 5 are replotted in Figure 6. Here the ordinate is the apparent SIF normalized with respect to the through the thickness value at the stress freezing temperature. In this case, the center slice SIF exceeded the through the thickness value by about 7%. As can be seen from Table I, for the Type A specimens with w/B = 2.0, this figure was 10% for all crack lengths between a/w = 0.5 and 0.7. However, for the type B specimens with w/B = 3.5, the excess of the center slice SIF over the through the thickness value varied from 5% for a/w = 0.5 to 10% for a/w = 0.7. Since experimental error, on occasion, can accrue to as much as 5%, the authors do not feel that the crack length effect, noted here, is particularly significant.

A comparison of the room temperature test results with the ASTM E 399-72 equation is found in Figure 7. Because of the high sensitivity of the Type A tests to the load alignment, two test specimens were tested independently at each value of a/w in order to insure more reliable SIF values and each point on the w/B = 2.0 curve represents the average of two tests. For w/B = 3.5, pilot studies showed that one test was sufficient.

Results of the study may be summarized as follows:

i) For w/B = 2.0 and a/w = 0.50, experimentally determined normalized SIF values were only 2% higher than the ASTM E 399-72 values. In view of a possible 5% experimental error, this difference is judged to be negligible.

ii) Normalized SIF values over the a/w range of 0.3 to 0.7 for w/B = 2.0 averaged 5% higher than the ASTM E 399-72 result and, for w/B = 3.5, averaged 13% higher than the ASTM E 399-72 result.

iii) Center slice normalized SIF values were 5 to 10% higher than through the thickness average values for both w/B = 2.0 and w/B = 3.5 (See Table I).

DISCUSSION

The existing ASTM E 399-72 solution is supported by a very accurate boundary collocation solution of an idealized compact tension specimen geometry which has been verified by compliance measurements by Wilson [5] and his associates, by K calibration studies by Srawley and Brown and their associates, (unpublished) and by a recent finite element solution by Wilson and his associates [31] where he used linear strain elements in conjunction with a J Integral SIF determination. Quite recently, using a different approach, Newman [32] has used a boundary collocation solution to study effects of the pin holes for various a/w which generally agrees with the other two dimensional results.

The results cited in this study indicate that the ASTM E 399-72 result is quite accurate for w/B = 2.0 and a/w = 0.50. However, when the crack lengths are varied outside the ASTM allowable range of a/w = 0.45 to 0.55, higher values of normalized SIF result for w/B = 2.0 and still higher values result for w/B = 3.5. This suggests that if ASTM specimen geometry restrictions are to be relaxed, then additional analyses including three dimensional effects may be necessary to account for results observed here.

The above discussion is based solely upon linear elastic fracture mechanics since plasticity effects were not present in either the analytical or experimental models discussed here. In fracture toughness tests, however, plasticity is present and may exert a significant influence upon the test results if the models are not thick enough. Moreover, there is the question of the variation of constraint through the thickness in the thinner models and, in fact, whether or not plane strain predominates. Due to these complicating factors, the authors do not recommend prediction of fracture toughness results from their tests.

SUMMARY

A set of photoelastic experiments was conducted in order to study the influence of crack length and thickness upon the SIF for compact tension specimens within a crack length range a/w of 0.3 to 0.7 and for two thicknesses w/B = 2.0 and w/B = 3.5.

The experiments confirmed the validity of the ASTM E 399-72 solution within its limits, i.e. (w/B = 2, a/w = 0.45 to 0.55) but showed measurable increases in the normalized SIF for larger values of a/w and w/B. A variation in the SIF through the specimen thickness was also identified.

The authors estimate their results to be accurate to within about 5% for linear elastic fracture mechanics comparisons. Moreover, the differences in the SIF values for the two values of w/B were only about 8%. Even though the latter difference was established from average values of some dozen or more tests in each series, the authors recommend that further tests be conducted, particularly at values of w/B of 1.0 and 6.0, in order to determine if the trends observed here extend into those ranges as well as to further substantiate the present results.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the contributions of A. E. Harms and J. J. McGowan for their laboratory and programming assistance to the project. Collocation solutions for checks were graciously supplied by W. K. Wilson. The interest and support of N. G. Tupper, Al Gunderson and D. Frederick are also appreciated. This project was sponsored by the U. S. Air Force Systems Command, Wright Field, Ohio under Contract No. 33615-72-C2111.

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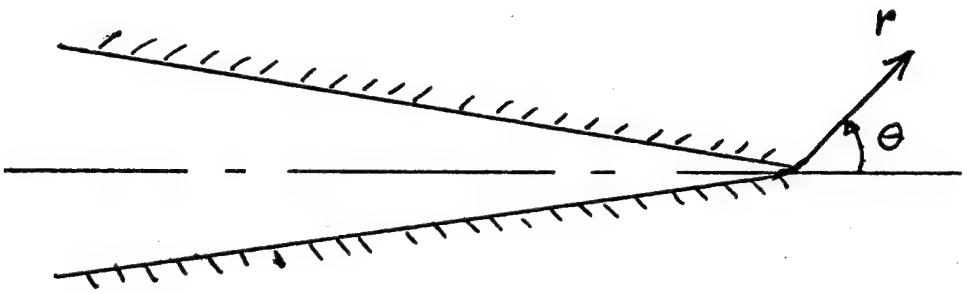

Fig. 1 Local Coordinates.

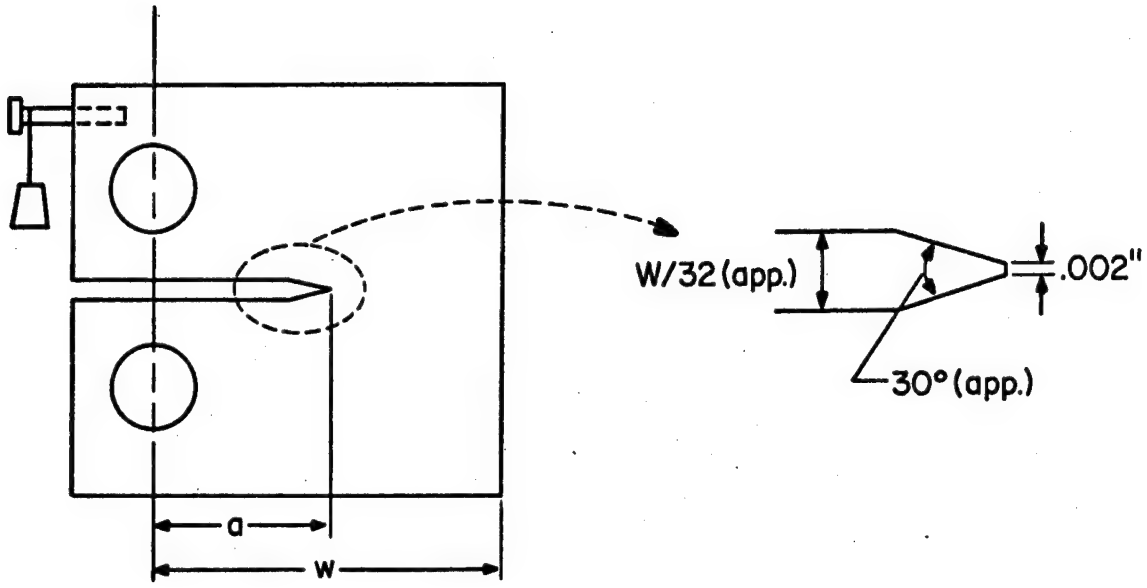

Fig. 2 Specimen Configurations

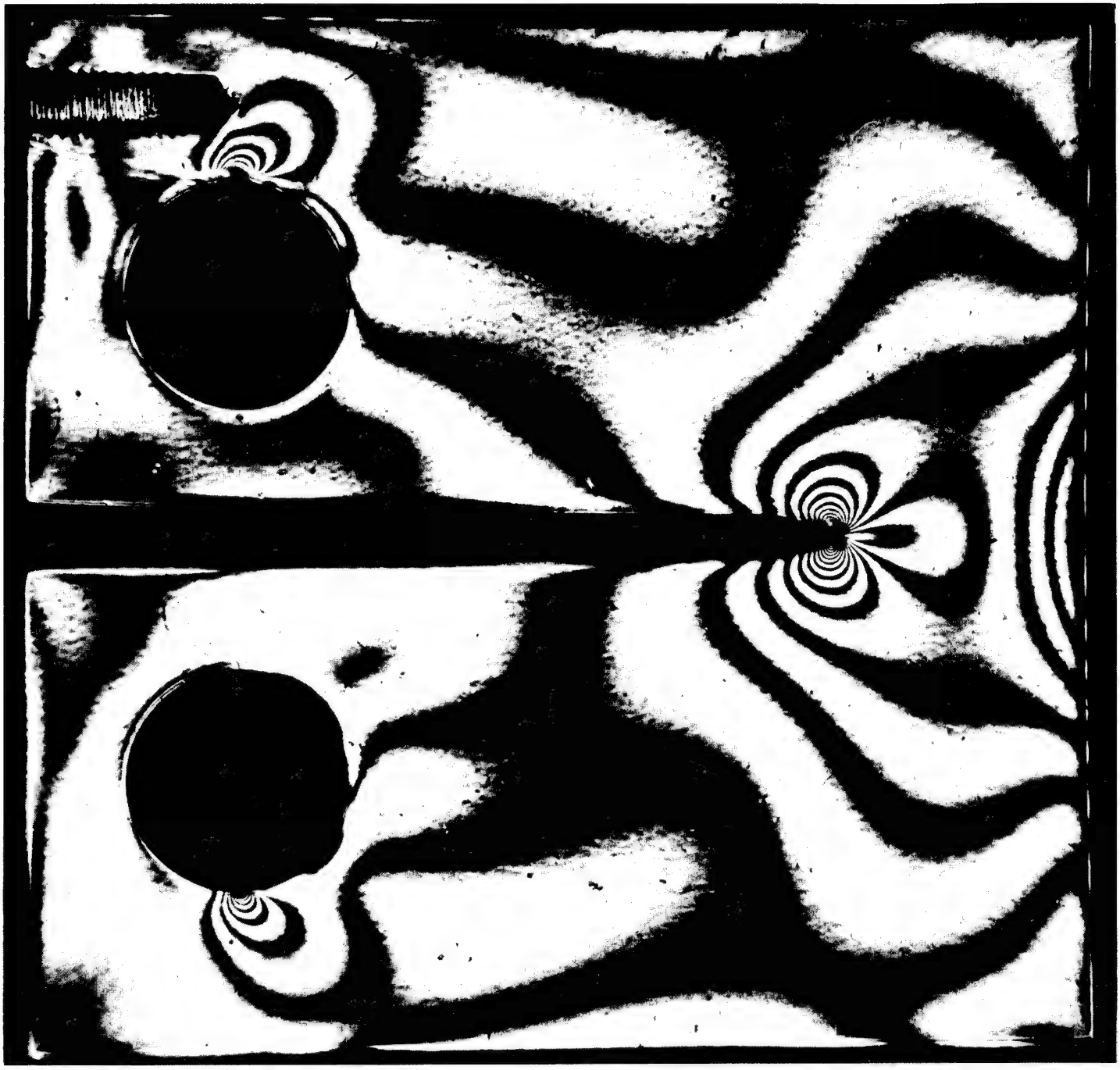

Fig. 3 Fringe Pattern of Full Specimen

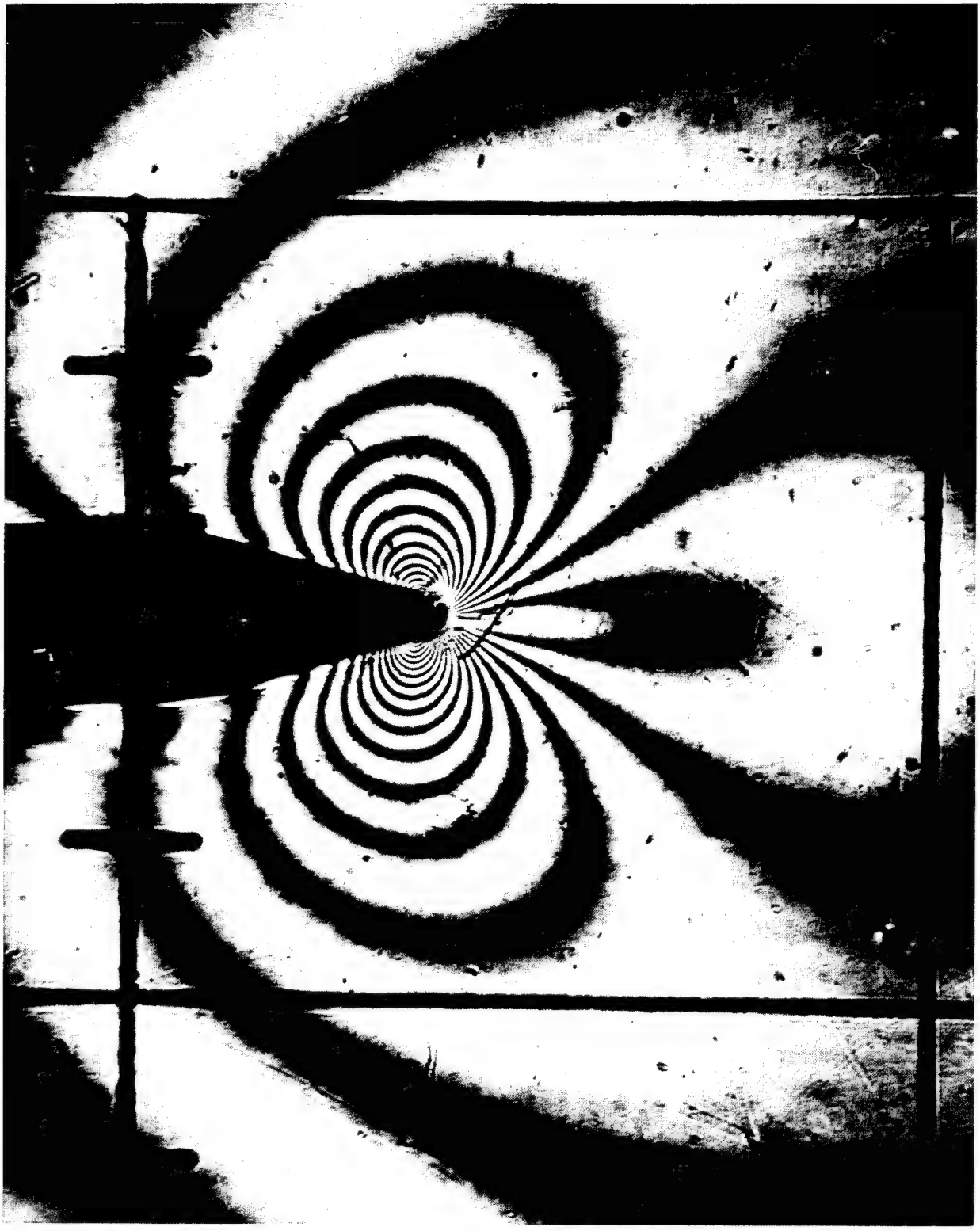

Fig. 4 Local Multiplied Fringe Pattern

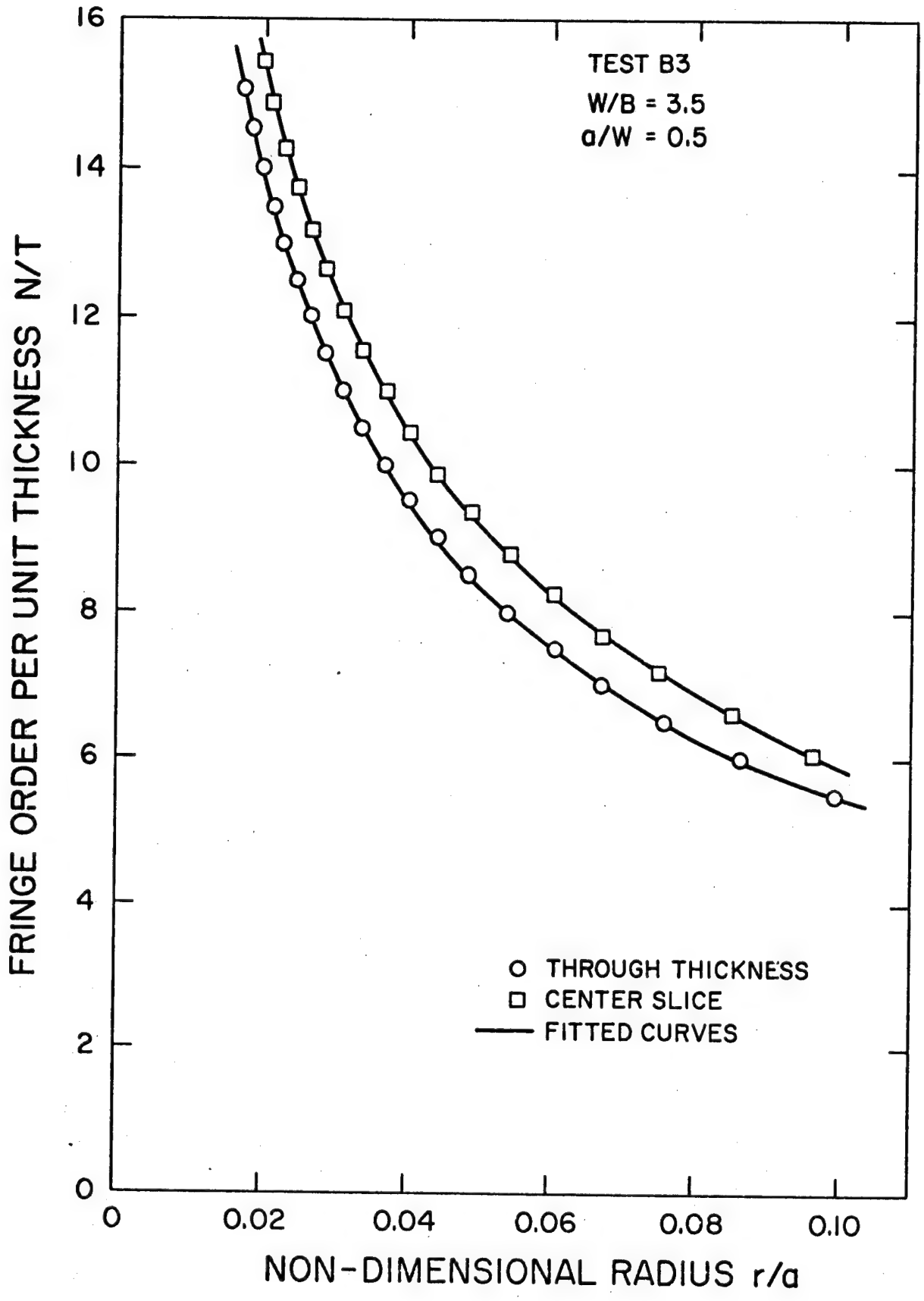

Fig. 5 Typical Set of Raw Data with Curve Fitted by TSCM

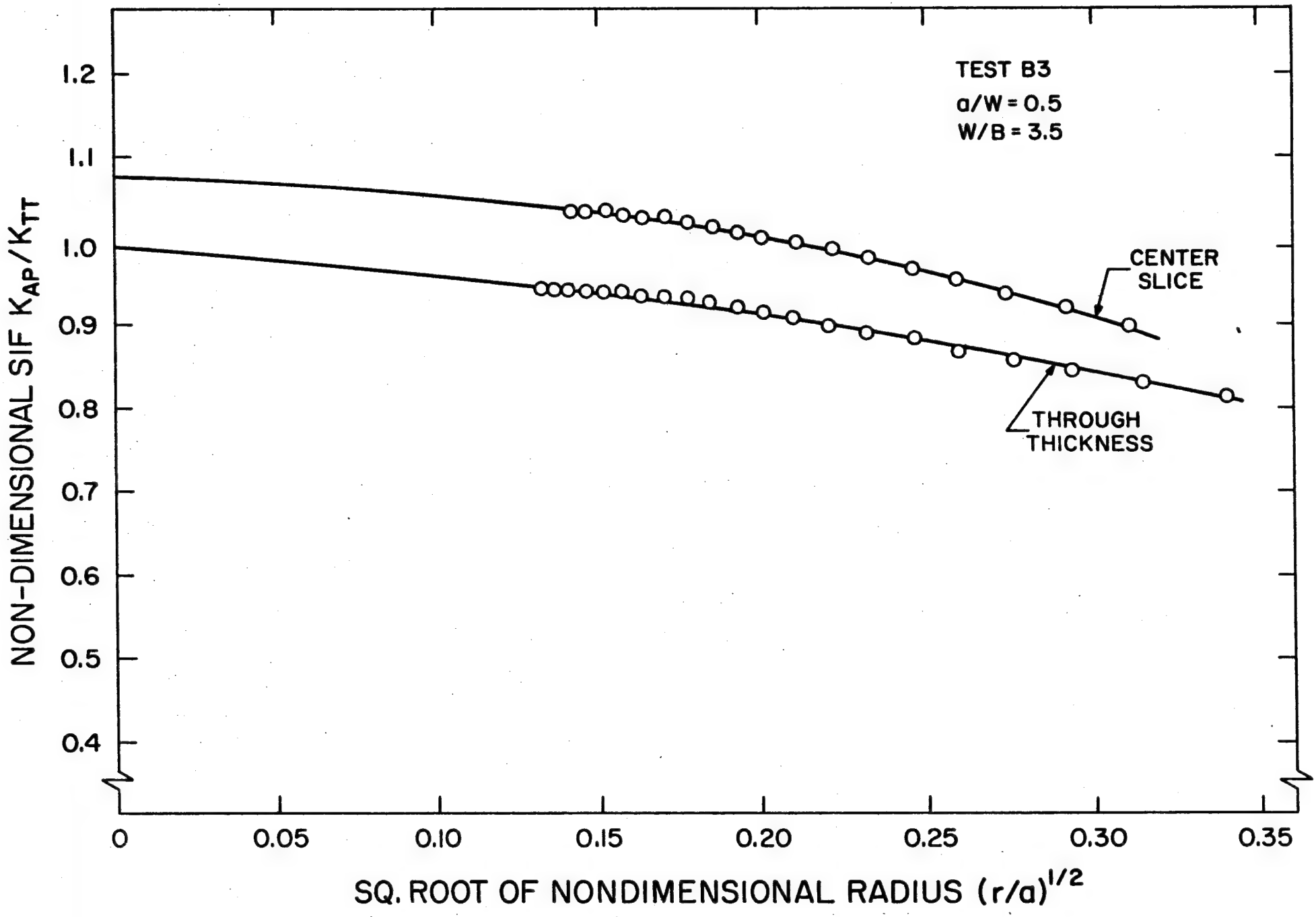

Fig. 6 Extrapolation from Data by TSCM to Obtain K_{TSCM}

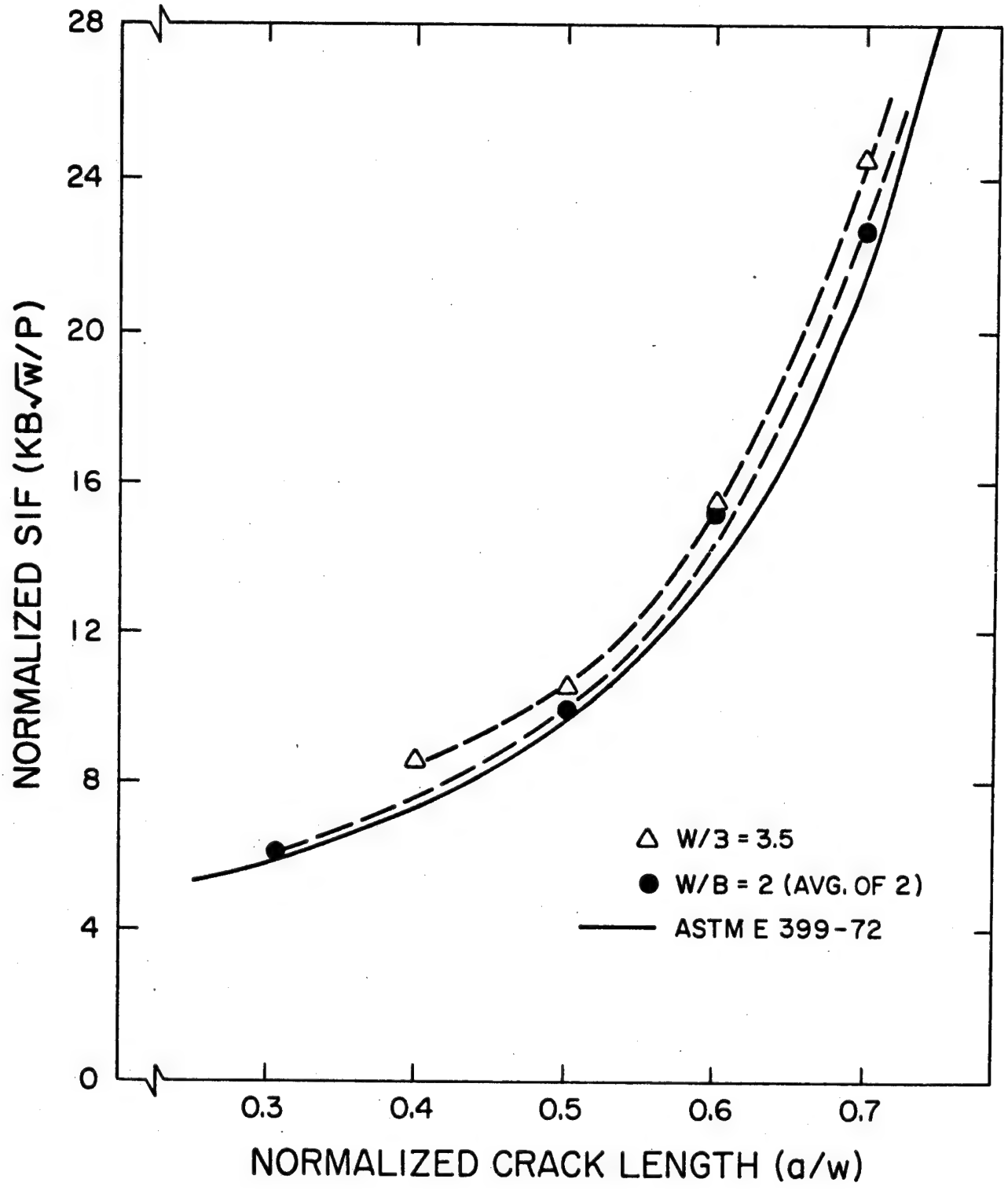

Fig. 7 Comparison of Results with ASTM Theory

TABLE I

	Geometry					Room Temperature Values		Stress Freezing Values	
Test	a(in)	w(in)	B(in)	a/w	w/B	$\frac{K_{exp} B\sqrt{w}}{P}$	$\frac{K_{theo} B\sqrt{w}}{P}$	K_{cs}/K_{TT}	
A-1	0.525	3.50	1.750	0.30	2.00	6.0	5.9	1.08	
A-2	0.875	1.75	0.875	0.50	↓	9.7[a]	9.6	1.10	
A-3	1.05	↓	↓	0.60	↓	15.1[a]	13.5	1.10	
A-4	1.23	↓	↓	0.70	↓	22.3[a]	21.4	1.10[b]	
B-1	1.40	3.50	1.00	0.40	3.50	8.4	7.3	1.05[b]	
B-2	1.58	↓	↓	0.45	↓	9.2[b]	8.3	1.06	
B-3	1.75	↓	↓	0.50	↓	10.5	9.6	1.07	
B-4	1.93	↓	↓	0.55	↓	12.3[b]	11.3	1.08[b]	
B-5	2.10	↓	↓	0.60	↓	15.6	13.5	1.09	
B-6	2.45	↓	↓	0.70	↓	24.5	21.4	1.10	

a = Average of two tests

b = Estimated or extrapolated from tests on similar or identical geometry

K_{exp} = Experimental SIF Averaged Through Thickness at Room Temperature

K_{theo} = Theoretical SIF ASTM E 399-72

K_{cs} = Experimental SIF Center Slice - Stress Frozen

K_{TT} = Experimental SIF Through Thickness - Stress Frozen

P = Applied Load

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*

Virginia Polytechnic Institute and State University

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

Influence of Three Dimensional Effects on the Stress Intensity Factor for Compact Tension Specimens

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

M.A. Schroedl and C.W. Smith

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
April 1973	20	32

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
No. 33615-72-C2111	
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Air Force Systems Command United States Air Force Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

The stress freezing technique of photoelasticity was utilized to study the stress intensity variation between full thickness and center slices of compact tension specimens for various crack lengths. Specimen geometries covered an a/w range of 0.3 to 0.7 and for values of w/B of 2 and 3.5.

Normalized SIF results for geometries within ASTM E 399-72 specifications (i.e. w/B = 2.0, a/w = 0.50) agreed with the ASTM solution to within experimental error. However, for a/w values outside the ASTM range (0.45 to 0.55), experimental results were measurably higher than the ASTM results for w/B = 2.0 and averaged 13% higher for all a/w studied at w/B = 3.5. The center slice SIF was found to be 5 to 10% higher than the through the thickness average on all tests.

DD FORM 1 NOV 68 1473 REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Stress Intensity Factor Compact Tension Specimen Photoelasticity Crack Tip Stress Fields						